

Blazar Flaring Rates Measured with *GLAST*

C. D. Dermer,^a B. L. Dingus^b

^a*Code 7653, Naval Research Laboratory, Washington, DC 20375-5352 U.S.A.*

^b*Los Alamos National Laboratory, MS H803 P-23, Los Alamos, NM 87545 U.S.A.*

Abstract

We derive the minimum observing time scales to detect a blazar at a given flux level with the LAT on *GLAST* in the scanning and pointing modes. Based upon Phase 1 observations with EGRET, we predict the *GLAST* detection rate of blazar flares at different flux levels. With some uncertainty given the poor statistics of bright blazars, we predict that a blazar flare with integral flux $\gtrsim 200 \times 10^{-8}$ ph(> 100 MeV) $\text{cm}^{-2} \text{s}^{-1}$, which are the best candidates for Target of Opportunity pointings and extensive temporal and spectral studies, should occur every few days.

Key words: Blazars, Gamma Rays

1 Introduction

The statistical significance for detection of a known source at the $n\sigma$ level is $n \cong S/\sqrt{B}$, where S is the number of source counts, B is the number of background counts, and the diffuse background is assumed to be precisely known (1). The observer is also assumed to follow a predetermined data analysis protocol and not to make multiple rebinnings of the data.

In this paper, we derive the minimum observing time for the Large Area Telescope (LAT) on *GLAST* (Gamma ray Large Area Space Telescope) to detect high-latitude γ -ray sources at given flux levels, and estimate the rate at which blazar flares at certain flux levels are expected to be observed with *GLAST*.

In Sections 2 and 3, we present calculations of signal and background counts, respectively. The five count and the five sigma requirements for detection are derived in Section 4. EGRET blazar studies, described in Section 5, are used to infer the probable rate of flaring emissions that *GLAST* will measure, as discussed in Section 6.

2 Source Counts S

The point-spread function (psf) of the LAT on *GLAST* is characterized by angle $\theta_{psf,G} = (3.5^\circ/57.3^\circ) (E/E_{100})^{-2/3} \equiv 0.061u^{-2/3}$, where $E_{100} = 100$ MeV and $E = E(\text{MeV})$ (2). We assume an energy-dependent analysis of the *GLAST* data, where the number of counts is integrated in the direction of a catalogued source over the solid angle $\Delta\Omega_G = \pi\theta_{psf,G}^2 = 0.012u^{-4/3}$. For this analysis procedure, the fraction f_γ of detected source photons is therefore independent of energy. For an azimuthally-symmetric, Gaussian distribution $\propto \exp[-(\theta/\theta_{psf,G})^2]$ of count directions, $f_\gamma = 1 - \exp(-1) = 0.63$, though $f_\gamma \cong 0.68$ would apply if θ_{psf} is defined as the 68% containment angle.

The number of source photon counts with energy $> E$ within $\Delta\Omega_G$ of a given point source is, in this approximation, given by

$$S \cong f_\gamma \int_0^{\Delta t} dt \int_E^\infty dE' A[E', \theta(t), \phi(t)] \phi_s(E', t) \quad (1)$$

where $\phi_s(E, t)$ is the source photon flux ($\text{ph cm}^{-2} \text{s}^{-1} \text{E}^{-1}$). We approximate the energy- and angle-dependent effective area of the LAT by the function

$$A(E) = A_0 u(\theta) (E/E_{100})^{a(\theta)} \cong X A_0 u^{a_0}, \quad (2)$$

where $u(\theta = 0^\circ) = 1$, $a(\theta = 0^\circ) = a_0$, and θ is the angle between the direction of a source and the axis of the LAT, and ϕ gives the azimuthal angle of the source with respect to the LAT orientation. Here we assume azimuthal symmetry of the detector effective area. An approximation for the effective area that satisfies the *GLAST* Science Requirements Document is $A_0 \approx 6200 \text{ cm}^2$ and $a_0 \approx 0.16$ for $100 \text{ MeV} \lesssim E \lesssim 10 \text{ GeV}$ (compare Foldout B in the *GLAST* proposal; this approximation breaks down above 10 GeV). For $20 \text{ MeV} \lesssim E \lesssim 100 \text{ MeV}$, $a_0 \approx 0.37$. The net observing time is denoted by $\Delta t = 10^4 t_4$ s, and the exposure factor X accounts for the fraction of time that a given source is being detected by the LAT. The effective area of the LAT drops by a factor-of-two at $\theta = 55^\circ$, so that we take $X = 0.2X_{0.2}$ with $X_{0.2} \cong 1$ in the scanning mode, noting that $\frac{1}{2}(1 - \cos 55^\circ) = 21\%$. (Signal detection on a 10^4 second time scale is of special interest in blazar studies, because the light-travel time across the Schwarzschild radius of a $10^9 M_\odot$ is $\simeq 10^4$ s.)

Normalizing the source flux to $10^{-8} \phi_{-8} \text{ ph}(> 100 \text{ MeV}) \text{ cm}^{-2} \text{s}^{-1}$, we have $\phi_s(E, t) = k u^{-\alpha_{ph}}$, where $k = 10^{-8} \alpha \phi_{-8} / E_{100}$. For $E > 100 \text{ MeV}$,

$$S \cong \frac{0.15}{g} f_\gamma (X_{0.2} t_4) \alpha \phi_{-8} u^{\alpha_\nu - 0.84}, \quad (3)$$

where $g = g(\alpha_\nu) = 1 - (\alpha_\nu/0.84)$. Here we use the following conventions to define the photon number index α_{ph} , energy index α , and νF_ν index α_ν : $\alpha = \alpha_{ph} - 1$ and $\alpha_\nu = 1 - \alpha = 2 - \alpha_{ph}$. For an intrinsic source spectrum with photon index $\alpha_{ph} \cong 2$, most of the photons are detected near the lower energy threshold.

3 Background Counts

The number of background photons with energies $> E$ observed during time Δt that lie within solid element $\Delta\Omega$ that is centered in the direction $\vec{\Omega}$ of a specified source is

$$B \cong \int_0^{\Delta t} dt \int_E^\infty dE' \Delta\Omega(E') A[E', \theta(t), \phi(t)] \Phi_B(E', \vec{\Omega}) , \quad (4)$$

where $\Phi_B(E', \vec{\Omega})$ is the diffuse γ -ray background in the source direction. A minimum level of background is provided by the diffuse extragalactic γ -ray background radiation, given by

$$\Phi_X(E) = k_x u^{-\alpha_B} , 0.4 \lesssim u \lesssim 700 \quad (5)$$

(3), where $k_x = 1.73 \pm 0.08 \times 10^{-7}$ ph (cm²-s-sr-MeV)⁻¹ and $\alpha_B = 2.10 \pm 0.03$. Other sources of background, in particular, the galactic diffuse γ -ray background, can also contribute; the > 100 MeV photon flux is \approx twice as bright at $|b| = 35^\circ$ and over 30 times brighter at the Galactic center than at the poles (4). A better estimate of blazar flaring rates must consider the galactic diffuse emission.

Considering only the extragalactic diffuse radiation and letting $\Delta\Omega = \Delta\Omega_G$, the number of background counts detected by *GLAST* is

$$B \cong 1.1 X_{0.2} t_4 u^{-2.27} . \quad (6)$$

This expression is valid for $1 \lesssim u \lesssim 100$.

4 Five Count and 5σ Criteria

The detection of at least 5 counts implies from equation (4) that $S > 5S_5$ with $S_5 \geq 1$ (the 5 count criterion), so that

$$(X_{0.2}t_4)\phi_{-8} \gtrsim \frac{34}{\alpha f_\gamma} gS_5 u^{0.84-\alpha_\nu} . \quad (7)$$

This expression fails for hard spectrum sources with $\alpha_\nu \gtrsim 0.84$, where cutoffs or breaks in the higher energy range of the spectrum and high-energy corrections to the *GLAST* effective area determine the number of detected source counts. Otherwise, most of the source counts are detected at the lower energy range near $E \cong E_{100}$. At energies below 100 MeV, the effective area declines more rapidly, so that most photons will be detected at even lower energies than 100 MeV unless $\alpha_\nu \gtrsim 0.63$.

Detection of a source with significance $> 5\sigma$ requires that $S/\sqrt{B} > 5\sigma_5$. Using expressions (4) and (7) for S and B , respectively, gives

$$(X_{0.2}t_4)\phi_{-8} \gtrsim \frac{1220}{\phi_{-8}} \left(\frac{g\sigma_5}{\alpha f_\gamma}\right)^2 u^{-2(\alpha_\nu+0.3)} . \quad (8)$$

By comparing equations (8) and (9), one sees that detection of soft-spectrum ($\alpha_\nu \lesssim 0$) sources with the LAT at the level of $\phi_{-8} \cong 15$, corresponding to the minimum flux sources that EGRET could detect in a 2 week viewing period, are background-limited near 100 MeV (that is, the time-on-source $X_{0.2}t_4$ is larger for the 5σ criterion when $u \approx 1$ than for the 5 count criterion).

For spectra that are not very soft (i.e., $\alpha_\nu \gtrsim -0.3$), the significance of detection increases with energy even as the source counting rate declines. Therefore there is a unique energy $\bar{E} = E_{100}\bar{u}$ at which both the 5 count and 5σ criteria for a source emitting at a given flux level ϕ_{-8} are satisfied, and this energy defines the minimum observing time to satisfy these criteria. For sources with $\alpha_\nu \gtrsim -0.3$, this energy is

$$\bar{u} \cong \left(\frac{36g\sigma_5^2}{\alpha f_\gamma \phi_{-8} S_5}\right)^{1/(1.43+\alpha_\nu)} \rightarrow 16 \frac{\sigma_5^{1.4}}{(\phi_{-8} S_5)^{0.7}} , \quad (9)$$

where the last expression applies in the special case $\alpha_\nu = 0$, $f_\gamma = 0.68$. When $\phi_{-8} = 15$, the energy to meet the two criteria is $\bar{u} \cong 4$, or the greatest sensitivity is at ≈ 200 -300 MeV. For sources softer (more negative) than $\alpha_\nu \cong -0.3$, energies near 100 MeV give the best sensitivity.

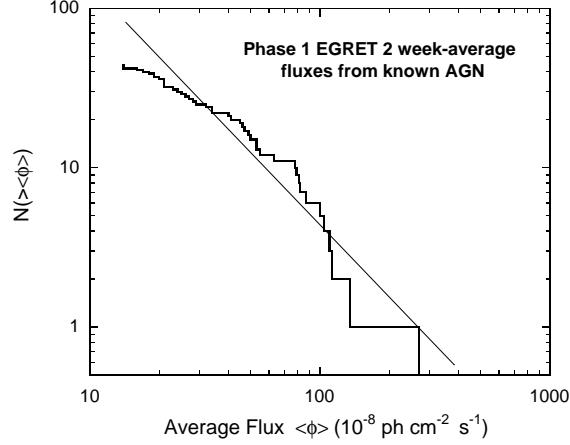


Fig. 1. The size distribution of blazar flares with 2-week-average fluxes $\langle\phi\rangle$ measured during the phase 1 EGRET all-sky survey (5). The straight line has slope $-3/2$.

The minimum observing time is given by

$$(X_{0.2}t_4)_{\min} = \frac{34}{\alpha f_\gamma} \frac{gS_5}{\phi_{-8}} \bar{u}^{0.84-\alpha_\nu} \rightarrow 7 S_5^{0.41} \sigma_5^{1.18} \left(\frac{\phi_{-8}}{15}\right)^{-1.59}, \quad (10)$$

where the right-hand-side is evaluated in the special case described above. Thus, *GLAST* will detect high-latitude sources at the level EGRET could reach in two weeks in only $\sim 7 \times 10^4$ s \cong 0.8 days, and it accomplishes this task in the scanning mode. Considering a background twice as large, which is more realistic for the majority of blazars, gives a detection of $\phi_{-8} \cong 15$ sources in \approx 1.2 days. Consequently, *GLAST* will scan the entire sky to the level of $\phi_{-8} \cong 15$ in a time slight longer than one day. For this, we can take the EGRET phase 1 catalog as a guide to what *GLAST* will observe.

5 Comparison with EGRET Phase 1 Catalog

Phase 1 of the *Compton Gamma Ray Observatory* observing program took place during a 596 day interval from 1991 April 22 - 1992 November 17 (5). Fig. 1 shows the size distribution of the two-week average fluxes of radio-loud quasars and BL Lac objects measured with EGRET during Phase 1, which consists of 44 high-confidence detections from 25 different blazars. Because the *CGRO* Phase 1 was an all-sky survey, it will be less biased to reveal the outcome of *GLAST* scanning observations than later EGRET catalogs where the number of detections is biased by the many pointings in the direction to previously known bright gamma-ray sources. Even so, the Phase 1 exposure

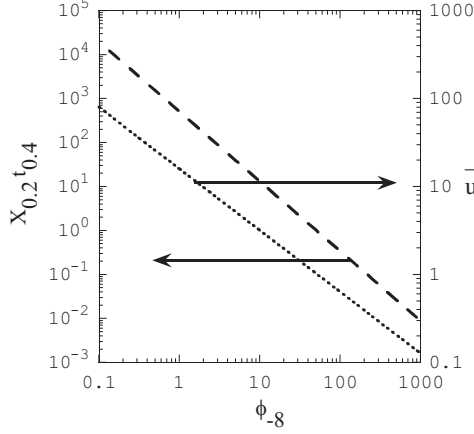


Fig. 2. Minimum required observing time for *GLAST* in scanning mode to satisfy 5 count detection, 5 sigma sensitivity criteria for a high-latitude source at the integral photon flux level $10^{-8}\phi_{-8}$ ph(> 100 MeV) $\text{cm}^{-2} \text{s}^{-1}$. Right axis is $\bar{u} = \bar{E}/E_{100}$, the photon energy in units of 100 MeV that satisfies these criteria in the shortest time. These results are for sources with flat νF_ν spectra, i.e., $\alpha_\nu = 0$, and assumes that only the extragalactic diffuse background contributes to background counts. The solution for \bar{u} is valid for $1 \lesssim \bar{u} \lesssim 100$.

map of EGRET is far from uniform. One must keep in mind that the two-week fluxes over shorter, brighter flaring phases, so that the estimated blazar flaring rate could be increased if the duty cycle of flares was better known citewal00.

The EGRET field-of-view was about 1/24th of the full sky, so that the Phase 1 duration was about twice as long as the time required to survey the entire sky with two-week pointings. During this time, EGRET detected some 3-10 sources at the level $\phi_{-8} \gtrsim 100$. Thus we expect *GLAST* to detect 2-5 such bright sources during a one-day scan. Although uncertain in view of the small numbers of blazars detected at bright flux levels with EGRET, one or two blazars brighter than $\phi_{-8} \gtrsim 200$ should be detected with *GLAST* every 3-4 days. A comparable number of unidentified γ -ray sources should also reach these levels (7).

6 Discussion

Fig. 2 shows the amount of time in the scanning mode required for *GLAST* to detect sources at given flux levels, using equations (10) and (11). Once the source flux $\phi_{-8} \gtrsim 200$, dozens of photon counts can be expected on a 10^4 second timescale. Changing to pointing mode for a non-Earth-occulted source will increase the source counts by a factor of ~ 3 -5, with the larger number

applying only to those few sources that are favorably located so that Earth occultation is not severe. At these flux levels, there are now sufficiently many photons to perform time-resolved spectroscopy. Sources exceeding the level of $\phi_{-8} \approx 200$ must be carefully and quickly reviewed to determine whether to issue an alert. Coordinated sensitive radio, optical, UV, and X-ray measurements would greatly strengthen tests of dominant radiation processes and inferred locations of the γ -ray emission sites. At these bright flux levels, $\gamma\gamma$ absorption and spectral evolution can be studied to deduce Doppler factors and monitor Doppler factor variations (8; 9).

Fig. 2 also shows that *GLAST* in the scanning mode will be sensitive to high-latitude γ -ray sources at the level of $\phi_{-8} = 2$ and 0.2 over ≈ 2 weeks and 2 years observing time, respectively. Thus *GLAST* will reach flux levels of $\approx 6 \times 10^{-13}$ ergs cm $^{-2}$ s $^{-1}$, fifty times fainter than EGRET's limiting sensitivity. As can be seen from Fig. 2, good low-energy (< 100 MeV) response and calibration of the LAT on *GLAST* are important for identifying transients on the shortest time scales.

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